Robert B. Wardle
Thiokol Propulsion
Manager, Propellants, Explosives, and Pyrotechnics Research Department

Principal Investigator on 22 Department of Defense contracted programs with an aggregate value of over $20 Million. Programs are research on the synthesis and evaluation of new ingredients for application in propellants, explosives, and pyrotechnics. The projects have included chemical process development and optimization for commercial synthesis of new ingredients.

Thirty-seven patents or patents pending in the areas of new energetic materials, propellants, gas generants and explosives.

Author or co-author on over one hundred technical publications in JANNAF, ADPA/NDIA, ICT, Chemistry Journals and related.

Chaired ADPA Energetic Materials meeting in Phoenix, 1996. Organizer of CL-20 Symposium, November 1997. Chair of numerous meeting sessions for ADPA, JANNAF, and ICT Conference.

Tasked with developing and instituting corporate involvement with new energetic materials. Current major project is construction of $3M pilot plant for production of novel energetic materials such as CL-20, TNAZ, TEX, oxetane polymers, nitrate ester plasticizers.

Education:	B.S. 1981, Ph.D. 1986 California Institute of Technology in Chemistry
Years at Thiokol:	13

Recovery and Recycling of Energetic Materials

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Thiokol Propulsion
From Cordant Technologies

Propellant Manufacturing and Life Cycle

- **Current solid propellants are typically cast cure systems**
  - Thiokol has demilitarized over 21 million pounds
    - well over 4200 rocket motors
      - 19 different configurations with steel and composite cases)
    - recovering as many ingredients as possible
  - Current production systems still adding to stream
    - scrap from each shuttle flight set is 15,000-30,000 lbs
    - working on utilizing these ingredients in other ways
      - humanitarian demining effort
- **Many other propellants have challenges**
  - Russian liquid formulations
    - Thiokol (with team) developed chemistry to convert ingredients into economically viable products
- **Cost of handling waste propellant increasing**

Humanitarian Demining

TS-50 - Anti-personnel with ~1 g RDX

Shu - Anti-personnel with ~1/2 lb TNT

- **Low-cost tool for neutralizing mines in the field**
  - passed tests against wide range of mines at Ft. Belvoir
    - small anti-personnel to large anti-tank
  - extremely simple operation requiring minimal training
    - ignited by an electric match
    - placement with simple tripod
- **Uses scrap space shuttle propellant in a ‘flare’ configuration**

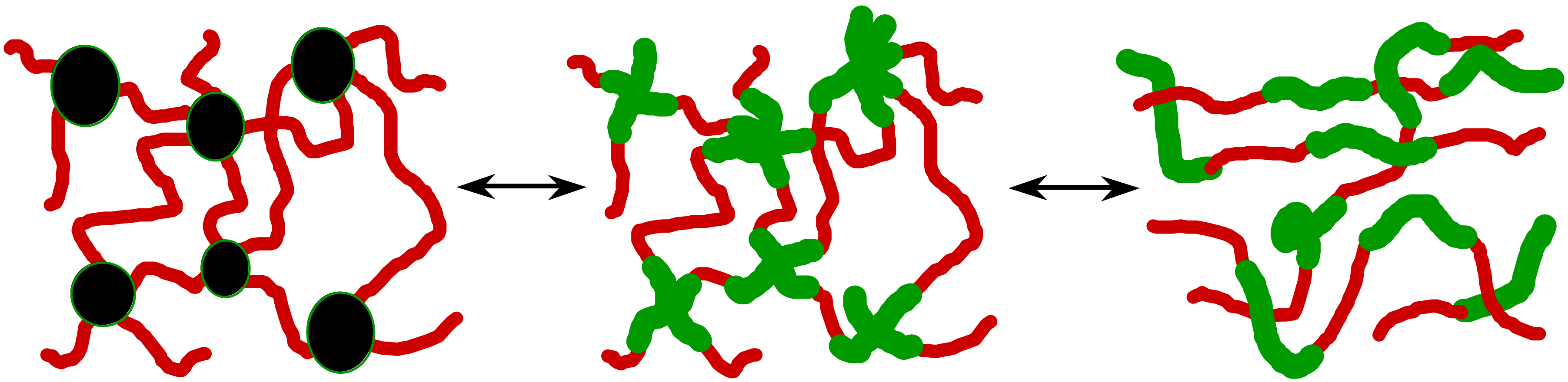
Processing Methods

- **New processing techniques (John Brough talk)**
  - continuous has the possibility to reduce waste
  - depending on the formulation other positive impacts
    - reduced hazards through reduced personnel exposure
  - Example: MTV flare formulation
    - current system uses 500,000 lbs of acetone and 3.8 million lbs of hexanes to produce roughly 225,000 lbs of formulation per year
    - Thiokol developing closed loop process for twin screw extrusion
      - increased safety and reduced environmental impact
- **Current binder systems have fundamental limitations**
  - cast cure like baking a cake - can’t unbake it
- **New processing alone will not address the fundamental issues regarding the materials**
  - need materials with characteristics fundamentally more suited to demilitarization
- **Into this already complex arena are thrust further requirements such as:**
  - reduced sensitivity
  - increased performance

Technical Approach

- **4th Generation Energetic materials**
  - environmental advantages by design
  - performance through chemistry and formulation
- **Use synthesis methods that reduce environmental burden**
  - reduce solvent usage
  - reduce aqueous waste
  - increase efficiencies
    - higher yield is lower environmental impact
      - cost trade-of can be surprising
- **Create formulations with long life cycle and low R3 costs**
  - find stable systems with low storage sensitivities
  - binder systems that allow multiple processes (TPE)
    - reduces scrap rate dramatically
    - allows reprocessing

Oxetane Thermoplastic Elastomers

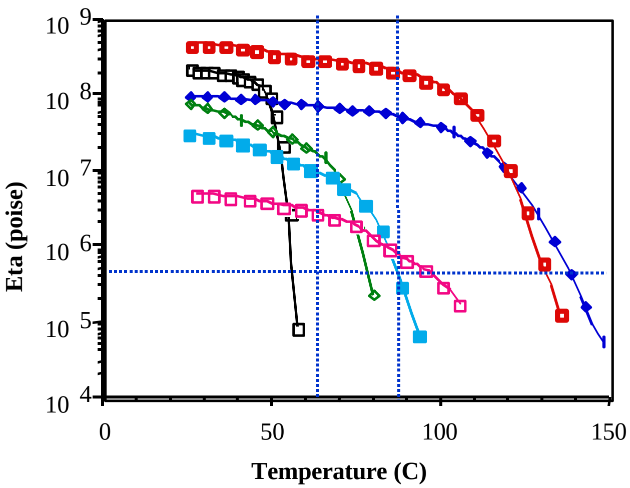


Below Tm of Hard Block
Hard Block Crystalline Sphereulites
Soft Block Elastomers

Above Tm of Hard Block
Hard Block Melts
Blocks phase separated

Flows and Mixes under Shear
Hard and Soft Blocks Mix
Annealing needed for phase separation

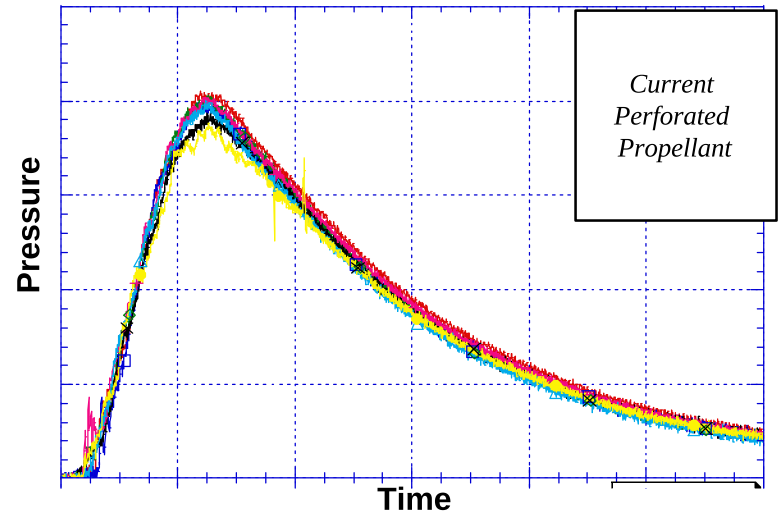
- Melting materials behavior critical to energetic processing
  - need narrow transition from hard to processible
  - m.p. too low and won't survive environment (<65C)
  - m.p. too high and energetic solids can't be processed safely (>90C)
  - dynamic viscosity data show attractiveness of crystalline hard block oxetane TPE (green line)
- Novel TPEs allow continuous processing and recycling
  - production scrap can be well below 1 percent
- TPE nature allows unusual geometries
  - better energy management maximizes performance

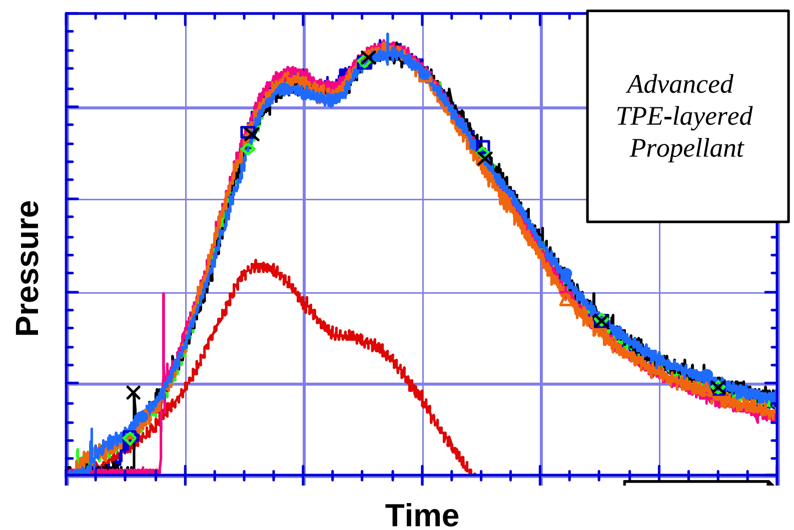


Example 1: TPE Gun Propellant

- Since 1995 Thiokol has produced over 1300 pounds of gun propellant containing a BAMO/AMMO TPE binder
  - Continuous processing allows use of high viscosity polymers like TPEs without processing aids
  - standard perforated grains and advanced geometries for greater progressivity based on application and need
- Thiokol has been reusing TPE propellants and components since 1995.
  - 15 lbs of CL-20 were removed from 7 perf grains without damage to the TPE binder and reused on ONR/ETC Program.
  - Made rolled sheet gun propellant from 7 perf grain propellant and reworked trimmings from disk propellant. Have used 300 lbs of propellant in these processes
- Demonstrated in 40, 60, and 120 mm gun firings.
  - Performance excellent

TPEs Improve Gun Performance





- Layered propellant demonstrates desired energy management in the 120 mm configuration used for Abrams tank type round
  - **dual burning rate allows maximum period at high pressure for increased muzzle energy**

Example 2: TPE Rocket Propellant

- **Formulation**

INGREDIENT	PERCENT
BAMO/AMMO TPE	20.00
Ammonium Perchlorate	63.37
Aluminum	14.63
TiO_2 (burn rate catalyst)	2.00

- **Theoretical Isp Data**

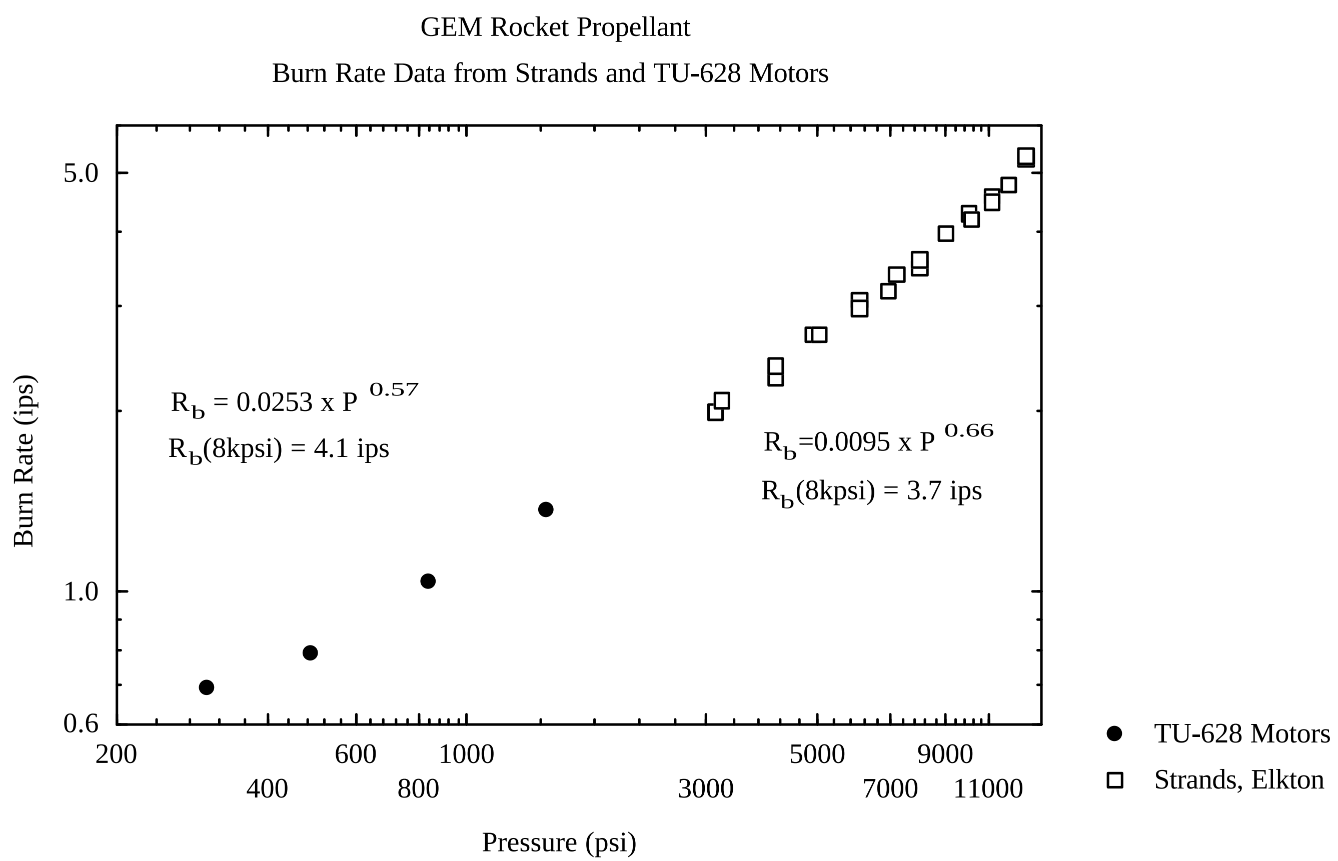
CHAMBER PRESSURE	EXHAUST PRESSURE	DENSITY	ISP	ISPXDENSITY
1000	14.7	.0664 (.0647)	259.2 (260.1)	17.2 (16.8)
8000	14.7	.0664 (.0647)	299.8 (301.5)	19.9 (19.5)

Values in parentheses are ERGM theoretical data

- TPE rocket propellant can exceed baseline (ERGM) performance with environmental advantages

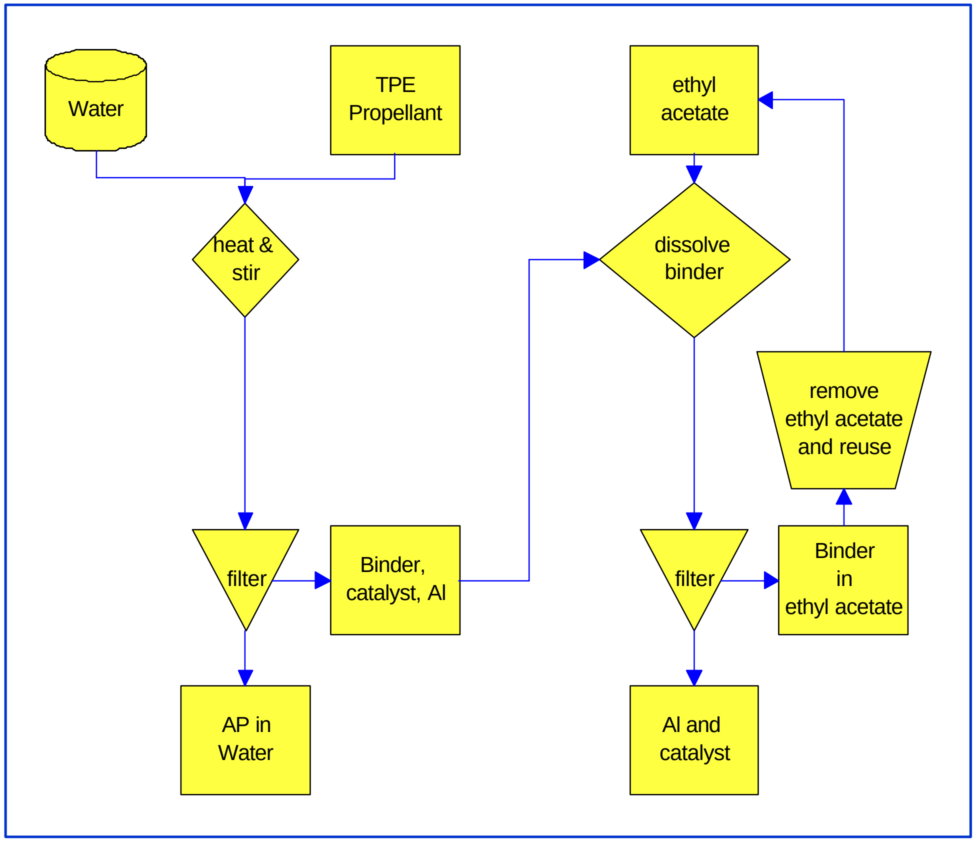
GEM Rocket Propellant Ballistics

- **Ballistic control in TPE propellant delivered**
  - high pressure needed for maximum performance
  - high pressure exponent or slope break will result in motor failure



Reprocessing, Recovery, and Reuse

- Have recovered and reused about 15 lbs of CL-20 from a BAMO/AMMO gun propellant
- Have reprocessed 300 lbs of gun propellant simply by melting the propellant.
- All ingredients in a TPE propellant can be reused, because no ingredients are destroyed in the process.
- Demonstrated the following ingredient recovery method on the GEM program



Reprocessing, Recovery and Reuse

- **Lab Scale Demonstration**
  - BAMO-AMMO/TiO_2 recovery
    - 105.7 % recovered (remaining solvent)
    - trace (19.42 ppm) AP remaining in BAMO-AMMO
    - TiO_2 can be recovered by centrifugation
  - Ammonium perchlorate recovery
    - 95.6 % recovered after water evaporation
  - Aluminum recovery
    - 61.7 % recovered after water evaporation
    - Loss due to fine particle size and transfer
      - can improve with better equipment

GEM Rocket Propellant: Demilitarization

- **Recovery and reusability of binder distinguishes TPE**
  - standard binder systems disposed of by incineration or landfill

Sample	Mn (1000s)	Mw (1000s)	Mw/Mn
Original TPE	21.4	116.2	5.43
Recovered TPE	21.4	115.9	5.43

- **Original TPE before being made into propellant**
- **Mixed into standard propellant**
- **Through aqueous recovery process**
- **GPC data side-by-side on same day/calibration**
  - these data so no damage in the polymer and predict properties in newly manufactured propellant will be the same

Recovered TPE is indistinguishable from initial material

Summary and Conclusions

- **Performance of energetic formulations cannot be overlooked or purpose is defeated**
  - increased demands on a wide range of munitions
- **Novel materials offer creative solutions to today's multi-faceted challenges**
  - ROI from Environmental improvements can be significant
    - John Brough presentation following
  - Performance can actually be improved as in examples shown
- **Opportunity is here to improve munitions of the future**